REVIEW ARTICLE

Three-dimensional Sonography in the Assessment of Normal Fetal Anatomy in Late Pregnancy

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Abstract

Three-dimensional, multiplanar sonography, using a volume data set acquired with a 3D probe, has revolutionized ultrasonographic imaging and takes sonographers to a new perception of the fetus in 3 dimensions. Real time scanning, until the late nineties only possible in B-mode, can now be performed in 3D with up to 40 frames/sec. Fetal neurology emerged as a new perinatal research field with the 4D visualization of fetal behavior. Doppler ultrasound, diversified and refined from continuous wave and pulsed Doppler to Color – and Power Doppler, when added to 3D sonography, creates fascinating options of noninvasive fetal vascular mapping (sonoangiography) and vascular assessment of placenta. The diagnostic and demonstrative potential of an acquired 3D volume data set can be maxed with the help of postprocessing and rendering software. After storage, the evaluation of fetal 3D data sets can happen without the patient, with the option of specialist consultation, using telemedicine. In the article, the new 3D "modes" like surface rendering, maximum mode, 3D Color and Power Doppler, STIC, volume rendering, and glass body rendering, are described and illustrated in their display of normal fetal anatomy.

Keywords: Fetal anatomy, 3D ultrasound, Sonoangiography, Power Doppler, Multiplanar imaging.

INTRODUCTION

More recent technological breakthroughs in diagnostic ultrasound have surpassed all expectations. With these advances, clinicians now have the tools needed to contend with many significant diagnostic challenges. However, these new technologies are so numerous and have been introduced in such rapid succession that considerable confusion surrounds their operation and application.

Indeed, with the advent and evolution of three-dimensional (3D) ultrasound technology over the last 15 years, we now stand at a new threshold in noninvasive diagnosis. The progression from two to three-dimensions has brought with it a variety of new options for imaging, storing and postprocessing of the ultrasound data. This technology gives ultrasound the multiplanar capabilities that were previously reserved for computed tomography and magnetic resonance imaging. In addition, it can generate surface- rendered and transparent views that provide entirely new diagnostic capabilities.

The main advantages of this new technology in obstetrics include improved assessment of the complex anatomic structures, surface-scan analysis of fetal fingers and toes, three-dimensional examination of the fetal skeleton, spatial presentation of blood flow information, and volumetric measurements of the fetal organs. When operating in multiplanar mode, the three-dimensional orientation of tomograms is unlimited, even with limited probe manipulation or inadequate position of the fetal structures. These imaging capabilities are extremely important during the first trimester of pregnancy when manipulations with the vaginal probe are restricted and obtainable ultrasound sections are limited.

During the transabdominal scanning, frontal planes parallel to the fetal abdominal wall that are unobtainable with conventional ultrasound became visible. Additional progress has been achieved through the possibility of eliminating surrounding structures. It has to be emphasized that, rather than representing an alternative, the three-dimensional technique is complementary to the conventional ultrasound technique in the field of prenatal diagnosis. However, 3D imaging is superior in solving specific diagnostic problems. A comparison of 2D and 3D techniques shows that in a large percentage of cases 3D offers a diagnostic gain owing to the possibility of surface- and transparent mode imaging.

As with any new technique, three-dimensional ultrasound scanning has some limitations. For example, fetal and maternal movements during the scanning process lead to motion artifacts that can degrade the image quality. Fetal surface rendering primarily depends on sufficient amniotic fluid volume in front of the region of interest (ROI). In some cases, oligohydramnios and superimposed structures like umbilical cord or limbs make surface rendering impossible.

Technological Improvements in Prenatal Diagnosis

Three-dimensional sonography (3D US) provides completely new modalities of sonographic scanning including coronal section imaging, three-dimensional reconstruction and volumetric calculation. Improved visualization rate, depiction of spatial relationship, "sculpture like" plastic imaging and volume measurement are the main benefits of new technology.

3D MULTIPLANAR IMAGING

Multiplanar imaging offers an option of synchronous scanning in three-orthogonal sections, including even coronal section (Fig. 1). Computer data processing provides numerous sections unobtainable by two-dimensional sonography (2D US). Multiplanar view results in a simultaneous display of three sections, one orthogonal to the others. Two of them (transverse and longitudinal) are dependent on the angle of insonation, whereas the third one (coronal) is not. This section is orthogonal to the insonation beam.

3D SPATIAL RECONSTRUCTION

Integration of data obtained by volume scanning can be used to depict 3D plastic (sculpture-like) reconstruction of region of interest (ROI). Three-dimensional reconstruction can be presented in surface or transparent mode. In the surface mode, only the signals from the surface of the ROI are extracted and displayed in plastic appearance (Fig. 2A). In transparent mode, the signals of highest and lowest echogenicity are extracted from the entire volume, resulting in possibility of spatial reconstruction of internal structure of ROI (Fig. 2B).[1] This mode is particularly useful for spatial reconstruction and imaging of fetal skeletal parts and their topographic relationship.

Spatio-Temporal Image Correlation Mode (STIC)

The breathtaking speed of progress in the development of computer technology with fast processors has led to further advancement of the ultrasound systems. Since 3D fetal echocardiography contributes significantly to the detection of cardiac malformations by visualization of the cardiac structures which cannot be demonstrated by 2D echocardiography alone (C plane in multiplanar imaging), and because 3D ultrasound is less dependent on the angle of acquisition, the introduction of the STIC technique to overcome non-gated acquisition artifacts in the reconstructed volume data due to the beating heart, was long awaited. The most promising aspect of this modality is possibility of storing and compressing a volume of 3D information for later offline evaluation by an expert, with the option of telemedicine.

STIC enables automatic volume acquisition by time-gated production of multiple slices of the beating fetal heart, which are then ordered according to their temporal and spatial reference within the heart cycle. The result is the volume of a complete fetal cardiac cycle displayed in motion in an endless 3D cine loop sequence. To achieve this, a single sweep recording 3D data set over an angle of 15-40 degrees is performed. This data set of multiple time-gated slices contains information of the entire fetal heart in motion, including the surrounding structures. If the

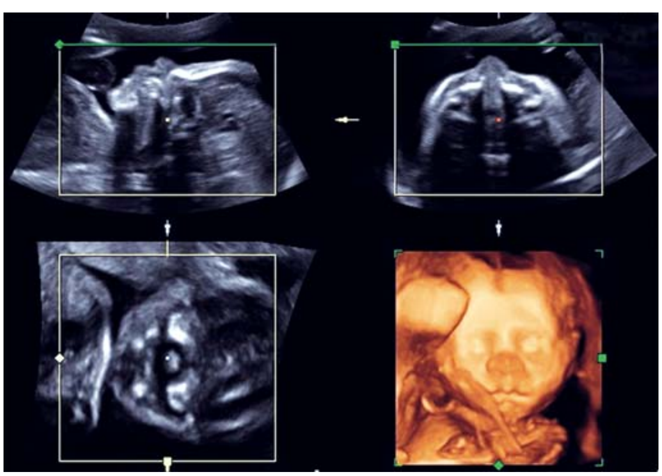
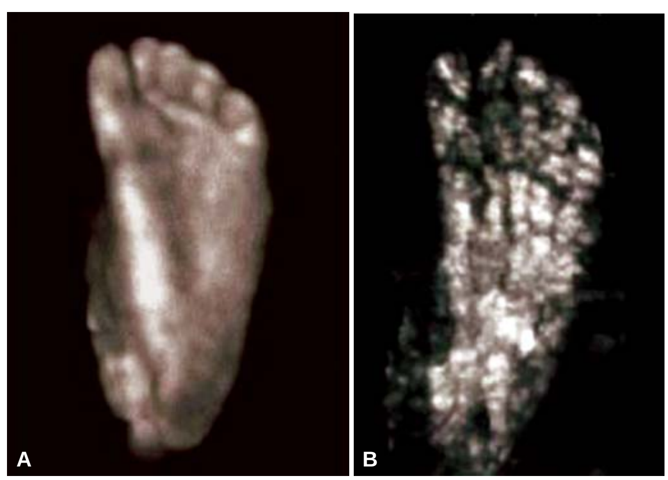


Fig. 1: Multiplanar view of the normal fetal face. Three orthogonal planes (frontal, sagittal, and coronal) and the final three-dimensional reconstruction are visible



Figs 2A and B: (A) Surface rendered fetal foot in plantar projection; (B) changing to transparent mode: normal skeletal structure and soft tissue are visualized

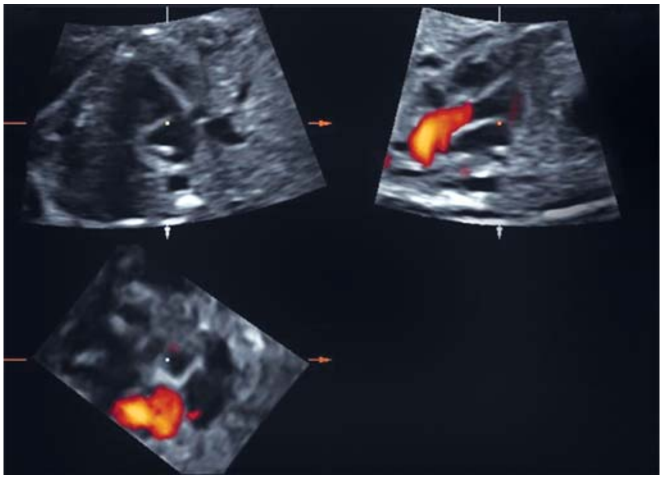


Fig. 3A: Left ventricular outflow tract (LVOT)

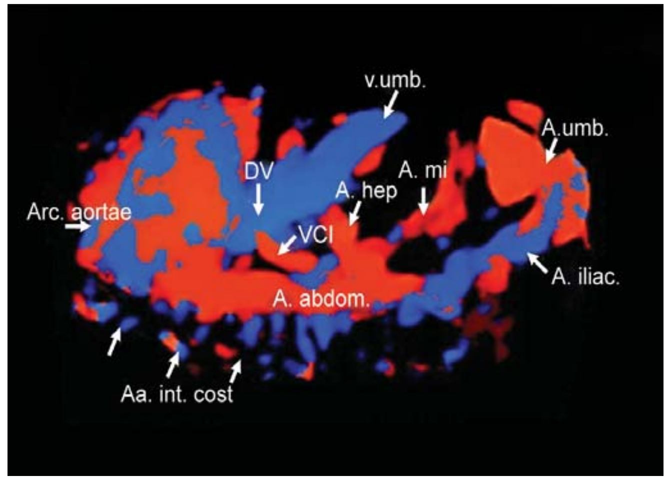


Fig. 4: Fetal vascular system visualized by three-dimensional color Doppler technique. Spatial reconstruction of the three-orthogonal planes. Color coding (blue—flow direction away from probe; red—flow direction towards probe) facilitates identification of vessels

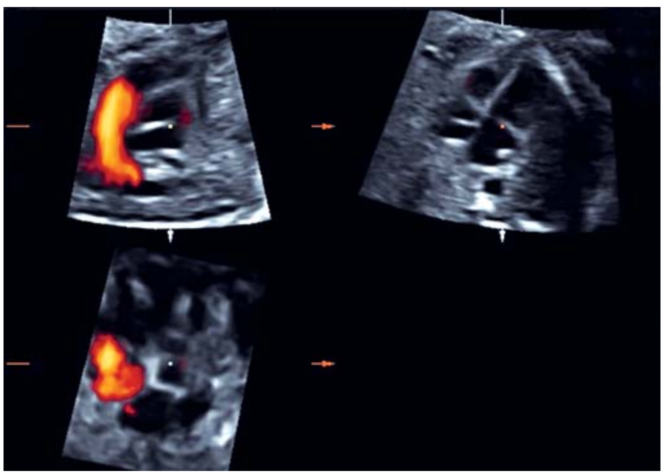


Fig. 3B: Right ventricular outflow tract (RVOT). LVOT and RVOT images are generated offline from the STIC volume data set after the patient has left

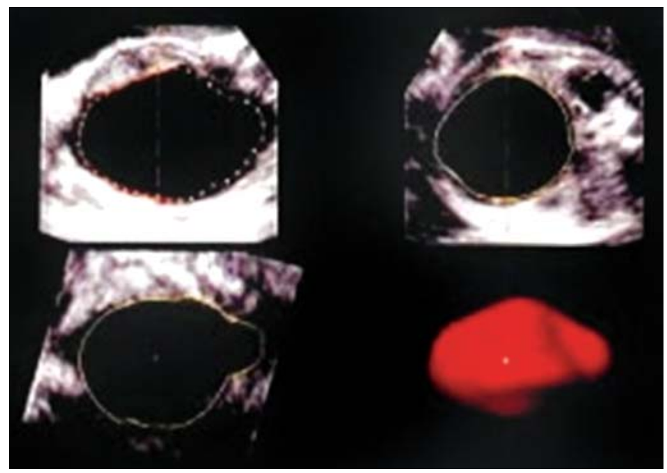


Fig. 5: Technique of volume measurement. The margins of a full fetal bladder are traced with cursor in three-orthogonal planes. Volume of the bladder is automatically calculated

acquisition begins at the level of the four-chamber view, which is usually recommended as a standard approach, a real-time motion sequence of a sweep from 15-40 degrees cranially and caudally from the four-chamber view is stored. This volume provides a multiplanar view of the heart in motion. Hemodynamic insights are gained by combining STIC with color and/or power Doppler mode. In addition, all existing rendering modes can be utilized to improve the diagnostic precision[2,3] (Figs 3A and B).

3D ANGIO MODE

Three-dimensional angio mode operates on technological basis of high-energy powered Doppler. Its greater sensitivity is related to direction independent scanning and better detection of smaller vessels. This mode provides optimal visualization and selective 3D reconstruction even of tortuous parts of vessels and of the blood flow arborization (Fig. 4).

DV—Ductus venosus; VCI—Vena cava inferior; A.umb.—Arteria umbilicalis; V. umb.—Vena umbilicalis; A.mi—Arteria mesenterica inferior; A. hep—arteria hepatica.

Three-dimensional (3D) reconstruction of the vascular signals has been accomplished utilizing the Doppler amplitude mode.[4,5] The implementation of the 3D color and power Doppler imaging permits the physician to investigate the anatomy and topography of hemodynamics within particular organ or ROI.

VOLUMETRIC CALCULATIONS

Three-dimensional measurement of organ volume (volumetry) is obtainable using sequential slice-stepping measurements of areas through the volugram of a targeted organ (Fig. 5).

The volume assessment by two-dimensional sonography (2D US) includes the approximation of volume based on the assumption that fetal organs have an ideal geometric shape. This however could be erroneous.

VISUALIZATION OF NORMAL FETAL ANATOMY

Two-dimensional sonography (2D US) is routinely used in obstetrics and has proved to be a powerful tool in clinical diagnosis and management. However, the ability to obtain certain views of the fetus may be limited because of its position or limited probe manipulations. Three- and four-dimensional US is advantageous in the workup of fetal anomalies involving the face, limbs, thorax, spine and central nervous system.[6] More realistic images contribute to the bonding effect between the parents and their future offspring. In addition, consulting specialists understand fetal pathology better and, if necessary, could better plan postnatal interventions. It is hoped that in the coming years this technique will be accepted by a large number of obstetricians, maternal fetal specialists and imaging specialists.[6]

Using 3D US any desired plane through the fetus is obtainable regardless of the fetal or probe position. Only the quality of imaging can be different depending on various sections. Therefore, in case of unsuccessful 2D US visualization additional information confirming normal fetal anatomy can be obtained by 3D US. The most common difficulties in 2D US scanning are related to visualization rates of the fetal face, mandible, lip, palate, tooth germs, distal part of the extremities, fingers and toes.[7-10] Depiction rate of these structures are significantly higher with 3D US (Table 1).[2,3,4,9]

Table 1: Visualization rates of fetal structures with two-dimensional and three-dimensional ultrasound

Structure	*2D US (%)*	*3D US (%)*
Tooth germs[9]	8.8	31.0
Upper lip[2]	93.0	100.0
Palate[2]	41.0	86.0
Distal extremities[3]	52.0	85.0
Fetal digits[4]	74.3	52.9

The data presented in Table 1 indicate that 3D US examination should be performed whenever 2D US is incapable to visualize these structures. Improved visualization rates of the detailed anatomy of the fetal face and extremities are closely related to the use of multiplanar imaging. Moreover, 3D US has greater potential to facilitate depiction of the distal segments of the upper and lower extremities and digits than 2D US. Depiction rate of the distal parts of the extremities is significantly higher with 3D US (85% *vs* 52%).[7] Ploeckinger-Ulm et al reported that the depiction rate of all digits was 74.3% by 3D US, compared to 52.9% by 2D US.[8]

An interesting point in the ongoing comparison of 2D and 3D/4D ultrasound was reached with the study of Goncalves et al.[11] They reviewed 706 articles on the use of 3D/4D ultrasound from the field of obstetrics. Their research concluded that 3D US compared with 2D, provided additional diagnostic information for facial anomalies, evaluation of the neural tube defects, and skeletal malformations. They concluded that more studies were required to find out, if the image information contained in a volume data set would alone be sufficient to evaluate fetal biometric measurements and diagnose congenital anomalies.[11]

One year later, the same research group evaluated a paradigm shift "What does 2D imaging add to 3D/4D obstetrical ultrasound?" After an initial 3D/4D volume sonography, 99 fetuses were then examined with 2D ultrasound. The frequency of agreement and diagnostic accuracy of the two modalities was calculated and compared to postnatal outcome. There was no significant difference in sensitivity and specificity between 3D/4D and 2D ultrasound. The authors concluded that diagnostic information provided by 3D/4D volume data sets alone did not exceed the information obtained by 2D ultrasonography.[12]

After Goncalves review in 2005, Kurjak et al analyzed the data from the literature published on the use of 3D US and 4D US in perinatal medicine. Out of 575 articles identified, 438 were relevant to their research definition. Their analysis revealed that 3D and 4D US is advantageous in evaluation of the facial anomalies, neural tube defects, skeletal malformations, congenital heart disease, central nervous system (CNS) anomalies and fetal neurodevelopmental impairment perceptible by abnormal behavior in high-risk fetuses.[13]

Visualization of the fetal face became one of the major interests in the domain of three-dimensional ultrasonography. Due to their affection in malformation syndromes and chromosomal abnormalitie, regions of special interest are fetal maxilla, mandible arch, ear and nose. Ulm et al reported better visualization rate of tooth germs with 3D US than 2D US (31% *vs* 8.8%)[9] Merz et al studied 125 fetuses to examine the effect of 3D US imaging on evaluation of the axis of facial profile.[10] They found that in 30.4% of the results, the profile section of 2D US facial profiles had a bias of 3-20º compared with an optimal mid-sagittal section obtained by 3D US. As a result, 2D US was able to obtain profile in only 69.6% of the fetuses. The importance of this finding should not be underestimated. When mid-sagittal plane could not be visualized, anomalies may be easily missed. Clearly, main improvement of 3D US is primarily related to facilitated visualization of the morphological details and complex anatomical structures.[14-16]

FETAL HEAD AND FACE

Assessment of the fetal head is an essential part of routine sonographic examination.[17] Even under optimal conditions, the position of the fetal head makes it difficult to obtain adequate images with two-dimensional ultrasonography, and many cross-sectional images are required to imagine the complete structure of the fetal head. Normal anatomy and major anomalies of the fetal head, such as exencephaly, anencephaly, encephalocele and holoprosencephaly can be recognized by detailed observation of the skull shape.[18] There are numerous reports about first trimester diagnosis of these anomalies using high-frequency 2D transvaginal sonography.[19-21] Surface rendering enables assessment of the shape of the fetal head, and detailed evaluation of the cranial flat bones, orbits, ears, nos and lips.[22] However, 3D sonography does not provide significant improvement regarding early diagnosis of major malformations. Surface rendered "sculpture-like" three-dimensional images represent the most impressive way of fetal visualization easily acceptable and recognizable even by parents. Ji et al conducted a study comparing the maternal-fetal bonding after 2D and 3D US imaging.[23] They found that 3D had a more positive influence on maternal-fetal bonding than 2D US.

Kurjak et al[24] evaluated the potential of 3D/4D US for the assessment of the structural and functional development of the fetal face. They considered fetal face as a "diagnostic window" for fetal diseases and syndromes especially in relation to the central nervous system (CNS). They found that 3D US has improved evaluation of the fetal facial anomalies. Four-dimensional ultrasonography allowed visualization of facial expressions that might be useful in evaluation of the fetal behavior, and contributed significantly to maternal-fetal bonding[24] (Figs 6A and B).

Surface mode is particularly useful for investigation of the neurocranium, sutures and fontanels which are flat and curved structures.[25] Cranial bone and suture assessment by 3D US is an important step in confirming normal morphology of the fetal skull.

Cranial sutures and fontanels are spaces between the fetal skull plates that allow progressive growth of the brain and skull bones during fetal development. At 12 weeks, premature cranial bones and sutures in between are detectable. The sagittal suture, lambda sutures and posterior

Figs 6A and B: Different fetal facial expressions. (A) demonstrates fetal smile; (B) visualizes scowling

fontanel can be recognized from 13 weeks. Therefore, fetal skull anomalies such as craniosynostoses can be excluded in late first and early second trimesters of pregnancy.[26]

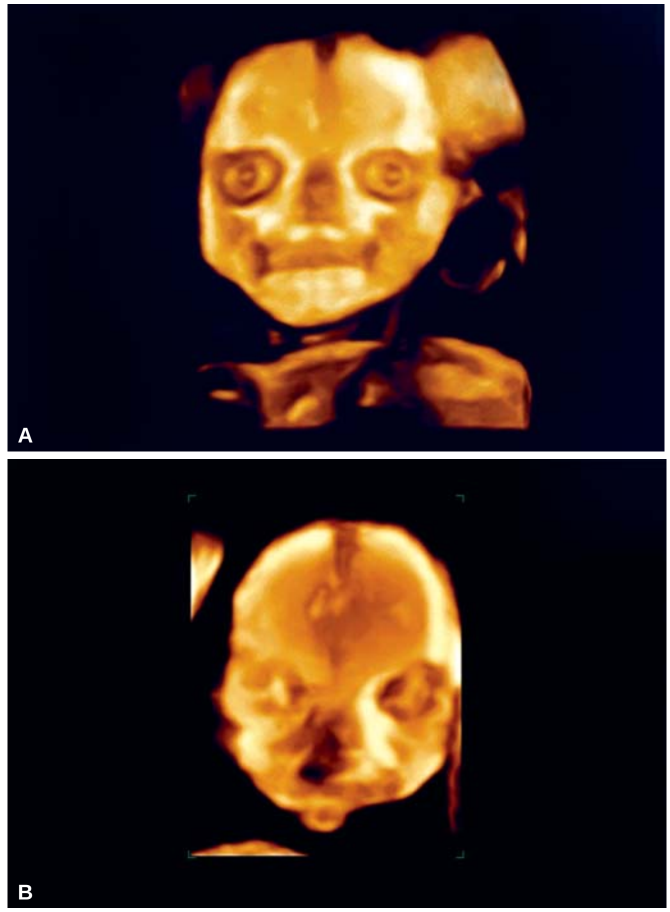
Sutures and fontanels can be identified with 2D sonography, when experienced sonographers target them. Unfortunately, sometimes it is difficult to assess the structural continuity of the sutures and fontanels with 2D US in a single plane because of physiological cranial curvature.[26,27] In general, real time 2D imaging permits the recognition only of their parts, whereas final impression about their integrity is a matter of sonographer's abstract thinking. Three-dimensional surface rendering of the fetal neurocranium allows visualization of the sutures, fontanels and flat bones on a single reconstructed image.

Fetal face can be identified usign 2D and 3D transvaginal sonography even at 10 weeks gestation weeks.[28] However, detailed observation and evaluation of the face can be accomplished between 22 and 24 gestational weeks.[29,30]

Facial examination can be performed only to a limited extent by 2D sonography, because of the facial curvatures and limitations of probe manipulation. Moreover, an unfavorable fetal position can make it impossible to visualize

Fig. 7: Surface rendered mode reconstruction of the fetal face. Facial structures and their spatial relationships are clearly visualized

Fig. 8: Surface rendered face of a fetus with opened eyes



Figs 9A and B: (A) Normal 3D reverse face view (3D RF) of the fetus seen in Figure 1. (B) Abnormal 3D RF view of the fetus with cleft palate

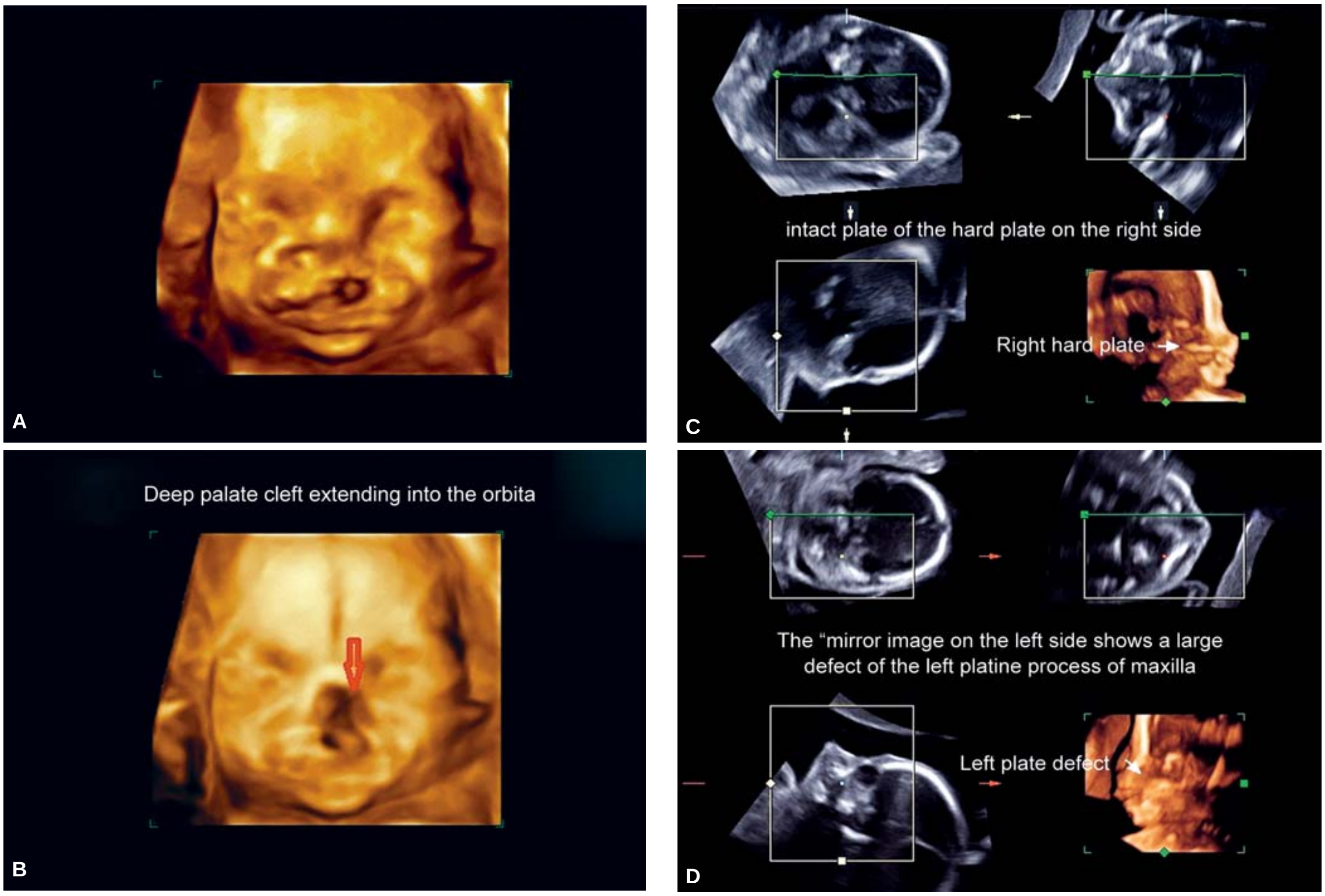
minute facial structures such as nose, eyes, periorbital region and orbits. Surface rendered images depict the entire face and relationship between the facial structures such as the nostrils, opened or closed eyelids and mouth on a single image. Moreover, depiction and observation of the orbital region and status of the fetal eyelids can be easily performed using this modality (Fig. 7).

Assessment of the facial structures is useful to detect unusual abnormalities.[31] Depiction of fetal eyelids is particularly good on a surface rendered view, as demonstrated on Figure 8.

Surface rendering of the fetal face allows images that are easy to understand. Perceiving the integrity of a face and interpreting facial expressions is an intuitive process that happens instantly. Therefore, it is much easier to use surface rendered images of the face in helping parents to understand the extent of craniofacial malformations of the fetus. Both 2D and 3D US are used to diagnose a cleft lip, however 3D US is superior to 2D in the detection and exact description of a cleft palate.[32]

Campbell et al.[33] reported on the use of "3D reverse face view" (3D RF) as an improved approach for the assessment of hard palate, not visible in the surface view of the face. The surface rendered frontal view of the face is rotated 180 degrees around the vertical axis until the face is seen "from behind". This technique assists in the antenatal categorization of the hard palate clefts (Figs 9A and B).

Beside normal morphology following anomalies can be detected by surface rendered examination of the fetal face: anophthalmia, microophthalmia, hypotelorism, hypertelorism, anterior or frontal encephalocele, exophthalmia, periorbital tumors, epignathus, teratoma and hemangioma. Sagittal view of the fetal face, facial profile, allows observation of the spatial relationship between the surface structures of the forehead and viscerocranium. Moreover, evaluation of the relationships between the structures of the viscerocranium including nose, lips and chin is easily performed (Figs 10A to D).



Figs 10A to D: (A) unilateral left facial cleft, surface rendered frontal view; (B) moving “into” the volume of the fetal face reveals deep cleft palate; (C) 3D multiplanar rendering demonstrates an intact hard palate on the right side; (D) rendering the “mirror image” on the left depicts partial lack of the hard palate

Even, the slight retraction of the inferior lip and chin in relationship to the upper lip can be recognized. A view of the profile allows prenatal diagnosis of the following anomalies: absence of the nose or nasal bridge, micrognatia and macroglossia. Clearly, the surface rendered image of the face is much more informative than a 2D image. This is of special interest in patients with family history of facial anomalies or in cases of maternal consumption of teratogens. Unfortunately, optimal visualization by this mode can be achieved only in 72% fetuses scanned between 20 and 35 weeks.[34]

Surface rendering image in combination with multiplanar views can reassure the ultrasonographer that lost signals in facial defects are not due to transducer angulation, and that the view of the face is symmetric. Rotational images are particularly comprehensive to parents, because they allow better understanding of the fetal anatomy and anomalies, if present.[29] It is well-documented that anomalous shape, size and position of the fetal ears are associated with a number of morphological and chromosomal syndromes. Prenatal assessment of the ear includes evaluation of ear morphology, size and position. Unfortunately, due to the complex shape, ear examination can be performed only to a limited extent by 2D US. In most cased 2D images are inadequate for precise evaluation of the ear morphology. Since only auricular geometry is visualized, the differentiation between variants of normal morphology and a dismophic ear is difficult. Surface rendering provides spatial reconstruction of the auricle and improves evaluation of the ear morphology (Fig. 11).

Furthermore, evaluation of the spatial relationship between the neurocranium and fetal ear can be obtained, including orientation regarding axis, location, length, width and area of the fetal ear.[35,36] By determination of the line between the orbits and peak of the auricle of the fetal ear we can assess normal and low-set ears. Low-set ears are associated with aneuploidies.[37]

Assessment of the fetal brain is an essential part of routine sonographic examination.[11] However, fetal brain can be examined only to a limited extent by 2D US. Observation

Fig. 11: Surface rendered mode reconstruction of the fetal ear. Ear morphology, position and size are easily evaluated

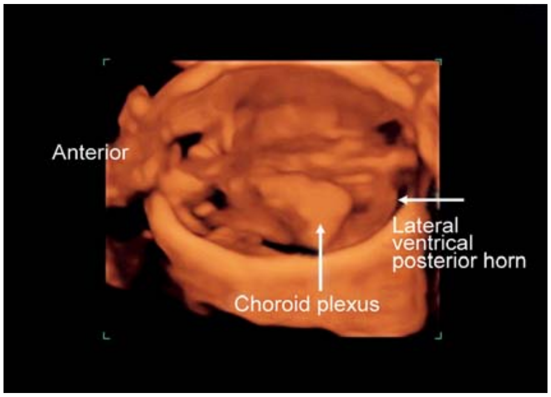
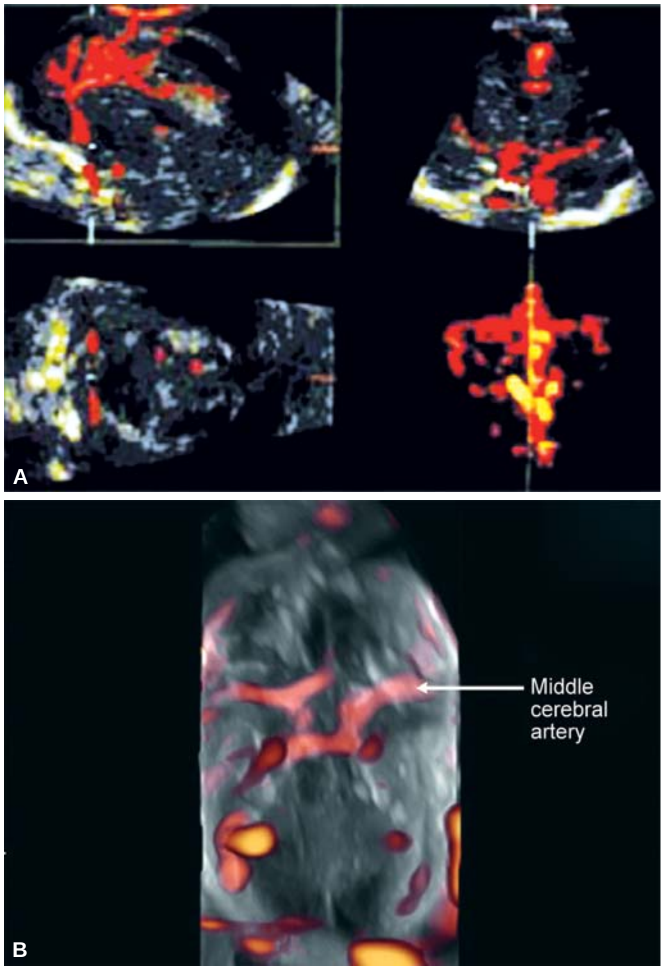


Fig. 12: Intracranial structures visualized by 3D ultrasound



Figs 13A and B: (A) Three-dimensional power Doppler image of the fetal brain (multiplanar analysis). In sagittal section pericallosal artery with branches is clearly visualized; (B) 3D power Doppler glass body rendering of the circulus arteriosus Willisii

of fetal the brain offers sagittal and coronal sections of the brain from fetal parietal direction through the fontanels and/ or sagittal suture as ultrasound windows.[38,39]

Three-dimensional sonography provides multiplanar analysis of the fetal intracranial anatomy. Moreover, rotating the brain volume image produces multiplanar image analysis of the intracranial structures in any cutting section. It is possible to demonstrate not only the sagittal and axial, but also the coronal section of the brain, which cannot be demonstrated from the parietal direction by conventional 2D transvaginal sonography[40] (Fig. 12).

The most impressive advancement achieved by 3D ultrasonography concerning prenatal neurosonography is the possibility to visualize the entire lateral ventricle including the anterior, posterior and inferior horns on single image. This section is called “the three horn view” and it is particularly useful for longitudinal evaluation of dimensions of the fetal ventricles.[41]

Transvaginal 2D sonography with color and power Doppler demonstrates sagittal and coronal images of the brain circulation.[42,43] Power Doppler images in midsagittal section obtained via the anterior fontanel demonstrate the internal carotid artery, the anterior cerebral artery, the pericallosal artery, the calloso-marginal artery and their branches. In coronal section, power Doppler images show the bilateral internal carotid arteries, the branches of the middle cerebral arteries and the anterior cerebral artery. Through the sagittal suture of the fetal cranial bone, power Doppler imaging demonstrates the intracranial venous circulation including the superior sagittal sinus, the internal cerebral vein, the vein of Galen, and the straight sinus. The main stream and the branches of the middle cerebral artery run in different directions, and both main line and branches cannot be detected in the same coronal section. This shortcoming of 2D US imaging has been overcome by reconstruction of the 3D power Doppler volume data showing the configuration of the brain vessels in three-dimensions (Figs 13A and B).

The internal carotid artery, anterior cerebral artery, bilateral middle cerebral arteries and their branches, can be demonstrated simultaneously on one image. Ultrasound angiography of the fetal brain allows noninvasive assessment of the brain circulation. Since 3D vascular images can be rotated in any direction, the vessels can be observed from the frontal, occipital, lateral, oblique, parietal or basilar part of the brain.

FETAL THORAX AND ABDOMEN

Due to the curvature of the thoracic bones detailed evaluation of the thoracic skeleton is often difficult with 2D US.[44] Three-dimensional US transparency mode reduces the echogenicity of the soft tissues, leaving behind echogenic structures, namely the bones, which enables visualization of the fetal ribs. The curvature and relationship of the ribs ending in the vertebral bodies and the anterior chest wall can be demonstrated in the entire length. Achiron et al evaluated specific advantages of certain 3D imaging and rendering modes for the optimal diagnostic display of certain malformations.[45] Volume datasets of 23 fetuses with thoracic anomalies were acquired with static 3D and cine 4D ultrasound, i.e. spatiotemporal image correlation (STIC) mode. The volumes were analyzed and displayed by multiplanar and tomographic ultrasound imaging (TUI) modes and static volume contrast imaging (VCI). Color Doppler was added to the volumes acquired, and various rendering modes were used to display the volume datasets. The TUI mode achieved optimal display of the thorax, thereby aiding the diagnosis of diaphragmatic hernia and lung dysplasia. High-definition color Doppler with glass-body rendering significantly contributed to the detection of abnormal vascularization in lung dysplasia. Maximal transparent mode by transvaginal route provided accurate diagnosis of skeletal dysplasia during the first trimester. Situs abnormalities were best visualized using minimal transparent mode. This modality has enabled clear identification of abnormal organs and positions of the vessels. Clearly, 3D/4D US enhances prenatal diagnosis and provides better spatial visualization of the thoracic anomalies.[45]

The organs of interest within the fetal thoracic cavity are the heart, with its chambers and outflow tracts, the aortic arch and ductus arteriosus, and the lung vessels (Fig. 14).

Although these structures are easily accessible by color/ power Doppler, especially for detection of the fetal heart defects or evaluation of the cardiac function, 3D ultrasound and power Doppler angiography are still developing. Fetal heart was poorly displayed by 3D ultrasound, owing to its motion during data acquisition. Using orthogonal triple-section display valves and running of the great vessels may be simultaneously assessed by scrolling the sections vertical to those corresponding to the four-chamber, five-chamber or short-axis views of the great vessels.[46,47] Zosmer et al observed intracardiac anatomy by transparency display and obtained high quality cardiac images at 20 weeks' gestation.[49]

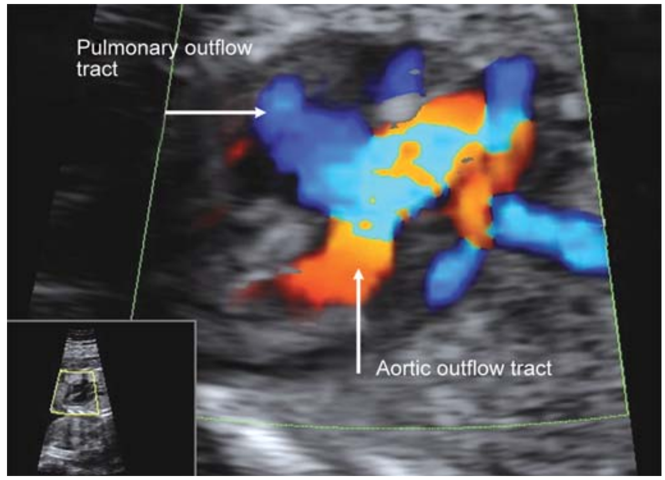


Fig. 14: "Crossing over of the fetal aorta and pulmonary artery" in color Doppler mode. "Color coding" of flow direction enables differentiation of the two outflow tracts

On the contrary, proximal and peripheral lung arteries and veins could be assessed from their origin to the peripheral pulmonary segments. Especially the right lung can be assessed even with little experience. Mitchell et al used color, pulsed and power Doppler to image the fetal pulmonary vasculature in normal pregnancies, but also in patients with pulmonary hypoplasia.[48] Compared to the normal fetuses, fetuses with pulmonary hypoplasia had a significantly higher resistance pattern of the Doppler signals obtained from the peripheral pulmonary arteries.

Power Doppler ultrasound produces impressive anatomic imaging with excellent demonstration of the fetal heart anatomy and delineation of heart borders. The anatomy of the great vessels is better understood by visualizing the crossing over of the vessels with and easy assessment of their size, course and shape. Visualization of the crossing of the aorta and pulmonary artery is facilitated with power Doppler technique due to the sharp edge definition. Another striking capability is display of both the left and right pulmonary veins draining into the left atrium. Such a clarity of images is difficult to achieve with conventional color Doppler imaging.

Using 3D power Doppler, Chaoui and Kalache demonstrated the fetal heart at 28 weeks' gestation in longitudinal view of the great vessels showing the right and left ventricular outflow tracts in their spatial relationship.[49]

The aortic arch and the crossing of the pulmonary trunk was clearly seen, as well as the connection of the ductus arteriosus to the descending aorta. The left pulmonary artery arises before the origin of the ductus arteriosus. Three-dimensional power Doppler approach enables imaging of the blood flow mainly in the center of the vessel, which assists in the spatial separation of the aorta and pulmonary artery despite high persistence. The expectation that 3D fetal echocardiography would include 3D power Doppler in addition to 3D or 4D gray scale, has come true with the introduction and perfection of spatio-temporal image correlation (STIC). It is expected that this modality will improve our understanding of the malformations such as hypoplastic left heart syndrome (HLHS), right heart syndrome, or other malformations with a singular ventricle and hypoplasia of the great arteries. The majority of the complex congenital heart anomalies show a steadily progression of the pathological changes during the course of pregnancy, including subsequent secondary phenomena such as arrhythmias or myocardial insufficiency. 3D/4D ultrasound is a tool of choice for follow-up of such a progression and may have a significant input in prenatal treatment of an abnormal fetus. Better understanding of the pathophysiological causal may encourage some researchers to explore new minimally invasive therapeutic options in terms of early pre- and postnatal cardiac palliation.[50]

Three-dimensional surface mode enables sculpture-like reconstruction of the abdominal wall and normal umbilical cord insertion. The complete abdominal surface is invisible by conventional 2D technology, unless the abdominal surface is scanned in a survey-like manner, involving serial tomographic sections in sagittal and transverse planes. Using 3D surface mode we are able to visualize the complete abdominal surface including a umbilical cord insertion in a single image. Using surface rendering mode continuity of the fetal skin can be easily confirmed.

Moreover, fetal fat deposits can be easily differentiated from abnormal protrusion caused by malformations and cutaneous or subcutaneous tumors.[51,52]

Postprocessing offers opportunity for surface imaging of the fetal intra-abdominal structures. Multiplanar imaging enables construction of the planes nearly parallel to the mother's abdominal wall, thus making it possible to observe the esophageal-gastric junction and pylorus. The electronic scalpel or electronic rubber is used to "cut out" the overlying body segments, producing either a longitudinal or transverse section. Once this has been done, the pathologic organ can be evaluated separately. Three-dimensional ultrasound confirms suspected multicystic dysplastic kidney as well as renal agenesis and abnormal pelvic-ureteral junction.[53]

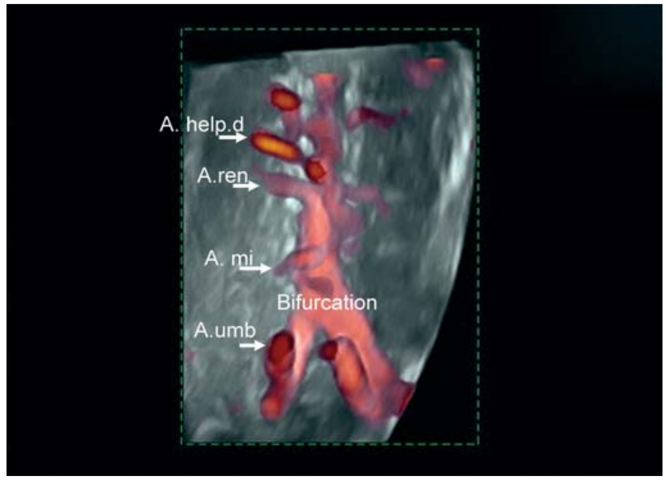


Fig. 15: Abdominal aorta and its branches in power Doppler glass body rendering. A.mi—inferior mesenteric artery; A.ren.—renal arteries; A.hep.d—right hepatic artery; A. umb.—umbilical arteries

Fetal intra-abdominal vessels are numerous and most of them can be visualized by color and power Doppler ultrasound.[54] The main veins of interest are the intrahepatic umbilical vein, the hepatic veins, the ductus venosus and the inferior vena cava. Another arteries that are commonly evaluated are the descending aorta and the superior mesenteric, renal, splenic, iliac and umbilical arteries. Owing to different velocities in these vessels and their different course, the examiner can focus on the region of interest by choosing the appropriate setting of the velocity scale as well as the insonation angle. Intrahepatic vessels are best obtained when the fetus is lying in the dorsoposterior position[42] (Fig. 15).

Longitudinal approach renders the best images of the insertion of the umbilical cord, the intra-abdominal course of the umbilical vein into the ductus venosus towards the heart, and the assessment of the relationship between the aorta and the inferior vena cava (Fig. 16).

In the lower abdomen a sagittal view allows visualization of the umbilical arteries circling the urinary bladder (Figs 17A and B).

The renal vascular tree is well-visualized in a coronal plane, with the descending aorta showing a horizontal course.[42] Depending on the pulse repetition frequency setting, the vessels can be seen from the main artery with some ramifications, to the peripheral cortical vessels including arteries and veins (Figs 18A and B).

The examiner should be aware of the possible false information given by the visualization of more ventrally situated abdominal arteries (inferior mesenteric artery and celiac trunk vessels).[26] These might be misinterpreted as renal arteries in some planes.

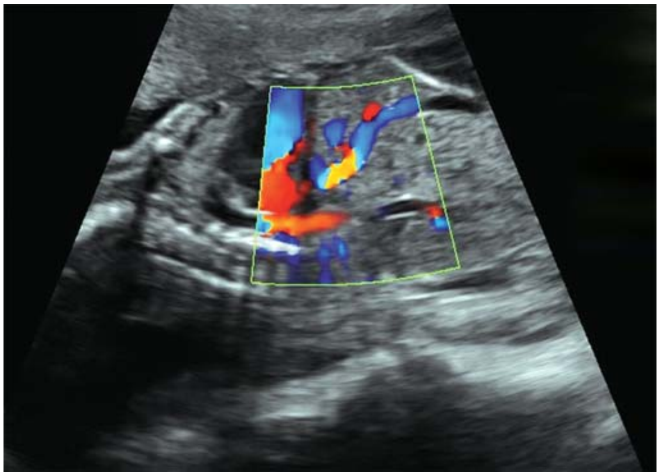
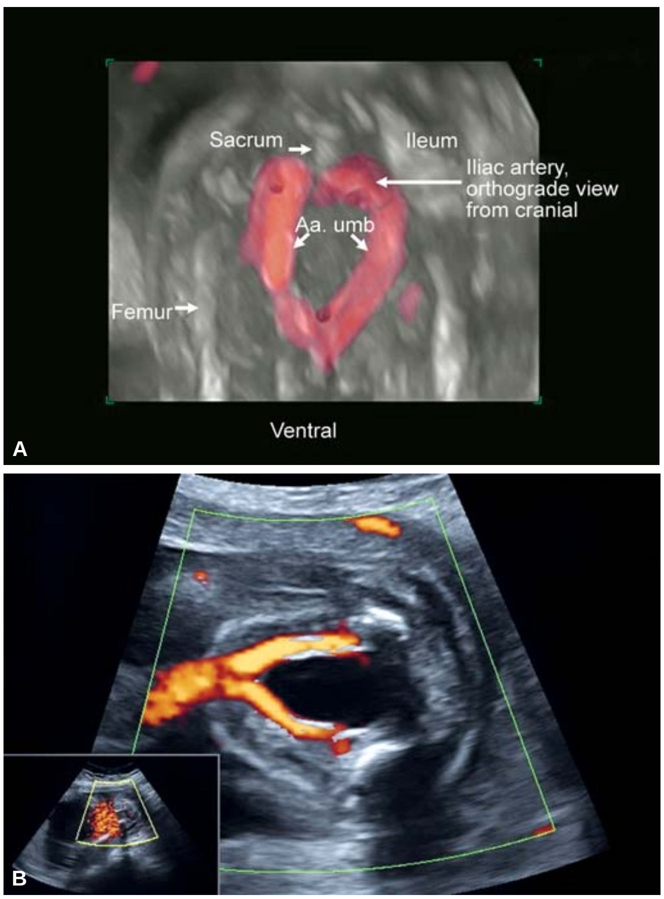
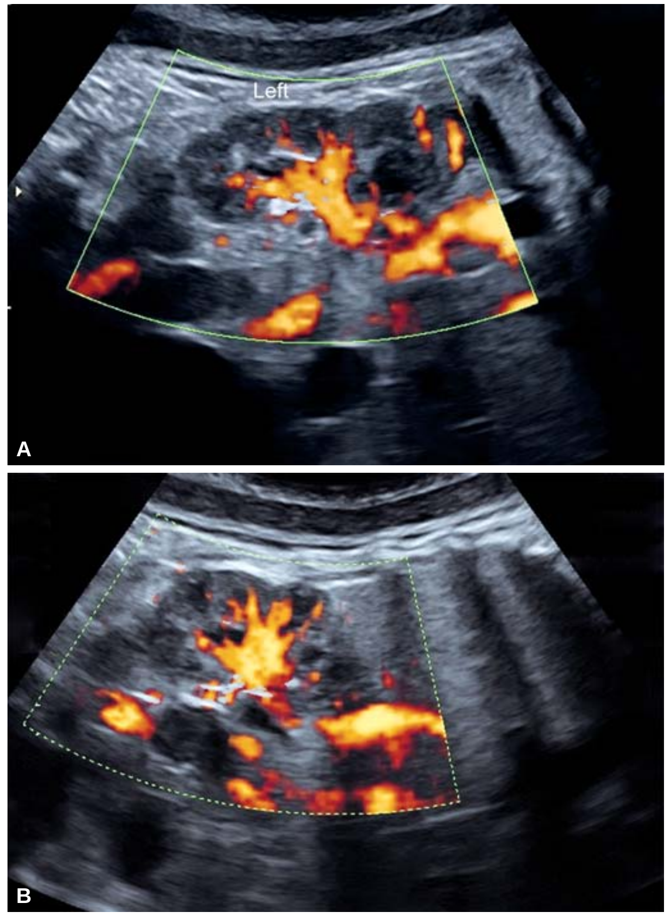


Fig. 16: Ductus venosus in color Doppler mode. Note the aliasing phenomenon in the continuation of the umbilical vein near the diaphragm, indicated by changing the colors from blue to orange. This color Doppler finding indicates turbulent jet in ductus venosus



Figs 17A and B: Umbilical arteries circling the urinary bladder in power Doppler 3D glass body rendering (A) and gray scale power Doppler mode (B)

This can be avoided by choosing a narrow sweep volume to avoid the imaging of non-renal vessels. To date, power Doppler imaging has been applied in fetal medicine as a qualitative imaging tool, whilst attempts at quantifying fetal blood flow have centered on comparing velocity measurements or ratios using spectral Doppler ultrasound. Modern digital imaging techniques nowadays allow extraction of the numerical information from the ultrasound images. Welsh and Fisk[55] assessed fetal renal perfusion by power Doppler digital analysis choosing a region of renal cortex for examination as the region of interest and extracting energy flow information. Integrated energy is plotted for the given region of interest where periodicity reflects fluctuations in a vascular volume within the arteries and veins, with systole, diastole and peak vascular volume appearing relatively constant throughout the central portion of the image.

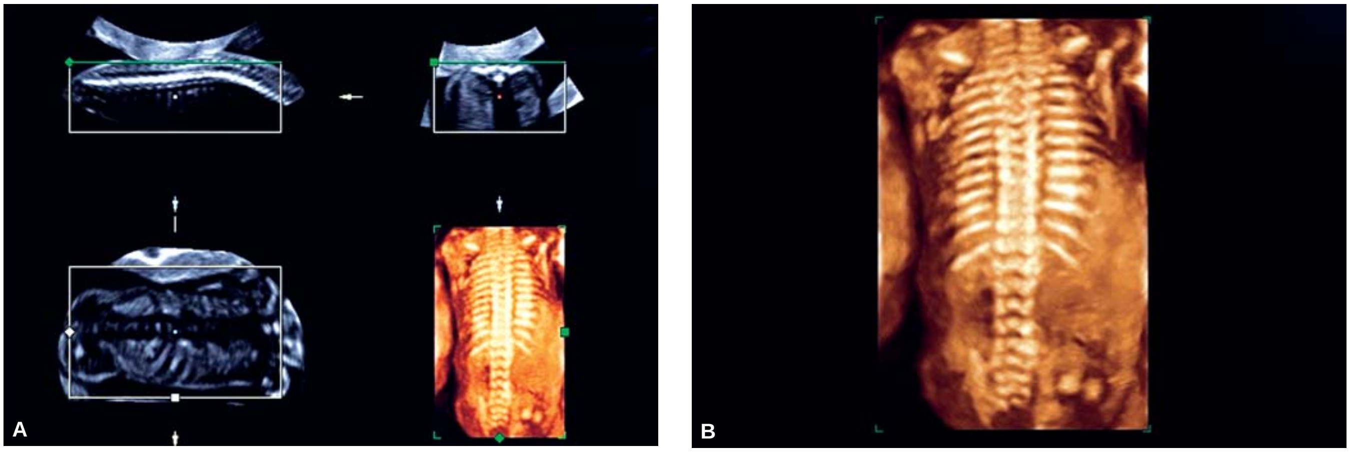


Figs 18A and B: Power Doppler image of the renal artery and its arborization within the left and right kidney

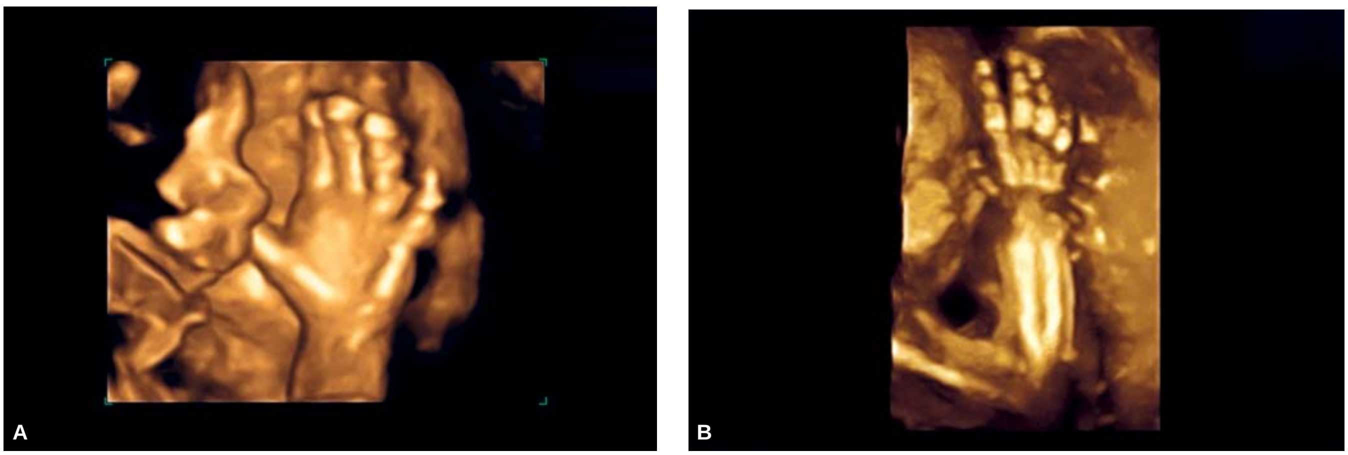
External genitalia can be clearly recognized by surface rendering, and complex malformations or developmental anomalies are diagnosed easily and much earlier than it was possible by he use of conventional ultrasound.[56]

SPINE AND EXTREMITIES

Particular importance should be given to visualization of the anatomy, spatial relationship, and angulations of the fetal



Figs 19A and B: Fetal spine in maximum mode. (A) multiplanar display; (B) maximum mode reconstruction from the three-orthogonal planes



Figs 20A and B: (A) Normal fetal hand reconstructed in surface rendered mode (B) Transparent mode reconstruction of the same hand and underarm, with clearly visible skeletal structures and soft tissue

skeleton by volume rendering using transparent mode, maximum mode and "X-ray-like" imaging.[57] This technique includes the volume rendered imaging possibilities between minimum and maximum intensity method (Figs 19 A and B).

3D-ultrasonography using transparent mode allows imaging of the fetal skeleton, and enables detection of the fetal skeletal malformations in spatial orientation. The vertebral column is originally curved antero-posteriorly. In fetuses with pathological lateral curvature 2D ultrasound cannot display the entire vertebral column in one two-dimensional tomogram. The advantage of 3D ultrasound is the ability to visualize both curvatures at the same time. Anomalies such as scoliosis, kyphosis, lordosis and spina bifida may be overlooked by 2D ultrasound, but are easily recognized using three-dimensional maximum mode. Congenital malformations of the fetal spine and ribs can be identified earlier using 3D surface imaging and transparent mode reconstruction simultaneously. Specific vertebral body level can be accurately identified by instantaneous demonstration of the axial planes within a volume rendered image or within the coronal plane image. It may be difficult to acquire the entire spine in a single volume, and thus multiple volumes are often necessary to completely evaluate the spine. An impressive example for transparent mode reconstruction is the complete skeletal "baby-gram".[22,27,58] Extremities consist of the three parts: the proximal, medial and distal part. Using this modality all three segments and spatial relationships between them could been analyzed in three dimensions. Therefore, deviation of the normal anatomical axis seen as pathological angulations of the fetal hands and feet can be excluded by 3D US examination.[59]

Three-dimensional images can be presented in two modes. If one is interested in spatial relationship between the segments of the fetal extremities, surface rendered mode should be used (Fig. 20A).

However, if the focus of interest is the relationship between the bone elements of the fetal extremity then transparent mode should be used (Fig. 20 B).

By combining these two modalities, more detailed analysis of the fetal anatomy is achieved. Distal parts of fetal extremities are clearly visualized by surface rendered reconstruction (Fig. 21).

Fig. 21: Surface rendered mode of the fetal legs. Normal anatomy and topographic relationships of the lower extremities are clearly depicted

Spatial relations between medial and distal segment of the fetal leg can also be assessed in surface rendering mode. Normal anatomical axis and axis deviations can be confirmed. Using three-dimensional ultrasound sonographer can evaluate fetal extremities from the external appearance to complex inner and intratopographic bone relations. Surface of the skin and external spatial relations are shown on surface rendering image, while complex anatomy of bone elements is better evaluated by transparent mode.

VOLUMETRY—ORGAN VOLUME MEASUREMENTS

Before the introduction of 3D US, organ volume measurements have not been widely used for the assessment of fetal growth and organ abnormalities, because of limitations of 2D US in estimating volumes of irregular structures. Comparing with 2D US, 3D US enables organ volume measurement by stepping through the fetal organs slice-by-slice. The area of interest can be traced by means of a cursor in each plane of the object. The total volume calculation is equal to the sum of the individual slice's volumes. Riccabona et al demonstrated both *in vitro* and *in vivo* that 3D US provides more accurate volume estimation of the structures with irregular shapes compared with 2D US.[60,61]

The feasibility of calculating the volumes of the following structures and/or organs has been reported: fetal lungs and fetal heart from second trimester to full term, placental volume, fetal arms, thighs, and renal and cerebellar volume for estimation of the fetal weight.[62-64] Of special interest are measurements of the fetal lung volumes in order to confirm or exclude fetal lung hypoplasia or immaturity.[65]

Three-dimensional US enables more sophisticated volume measurements of the irregularly shaped organs.[50,51] Lung and hepatic volume normograms have been published, showing that the volume of these organs increases with gestational age and weight.[63-65] After upper abdominal circumference, the best prediction of fetal growth restriction is the hepatic volume.[66] Therefore, hepatic volume may become a new useful parameter in the assessment of fetal growth. For many years fetal weight calculation has been mainly based upon abdominal circumference measurement. Among all possible sections and parameters of the fetal trunk, abdominal circumference has been chosen because it reflects changes of the liver size. This method does not consider the amount of the fetal fat tissue, and there is still no better discriminator for fetal growth aberrations.[67-69] Although neonatal fat mass represents only 14% of birth weight, it explains 46% of its variance.[70] Birth weight prediction based on limb volumetry including upper arm and thigh seems to be more accurate.[71,72]

CONCLUSION

The main advantages of three-dimensional sonography in prenatal diagnosis are:

1. Improved visualization and diagnosis (evaluation of the image planes that cannot be obtained with conventional two-dimensional imaging due to anatomic constraints and/or fetal position);
2. Easy demonstration of the coronal plane (the third plane, which cannot be displayed by conventional two-dimensional ultrasonography);
3. Transparent mode (particularly useful for imaging of the fetal skeleton);
4. Improved orientation and improved anatomic relationship by interactive rotation of volume rendered images;
5. Volume assessment;
6. Three-dimensional power Doppler reconstruction of fetal, placental and uterine vasculature; and
7. Analysis of fetal movement patterns by real-time 3D (4D) ultrasound.[73]

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